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CALCULATING THE BYPASS RATIO OF A TURBOFAN ENGINE BY USING THE ENERGY EQUATION

MICHAEL S. COALSON, CAPTAIN, USAF

TECHNICAL REPORT ASD-TR-68-1

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AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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ASD-TR-68-1

CALCULATING THE BYPASS RATIO OF A TURBOFAN ENGINE BY USING THE ENERGY EQUATION

MICHAEL S. COALSON, CAPTAIN, USAF

FOREWORD

The technique presented herein was conceived in May 1966 and first formally presented in a Technical Memorandum, SENX-TM-247. The technique was developed as the result of a need to determine the bypass ratio of an engine when data is inadequate for determination by the conventional method. Data from a TF30-P-1 engine obtained in tests conducted at the Naval Air Propulsion Test Center was used in the analysis.

This development was conducted in relation to Program 324A. The author served as project engineer for this phase of the program.

This report was submitted by the author in January 1968.

This technical report has been reviewed and is approved.

George F. Gillespie, Colonel, USAF
Director, Propulsion & Power Subsystems
Engineering
Deputy for Engineering
Aeronautical Systems Division

ABSTRACT

A method by which the energy equation is used to calculate the bypass ratio of a turbofan engine is presented. Only standard instrumentation is required for data except for that needed to measure the fan discharge total temperature. Results of calculations are presented and analyzed to indicate the sensitivity of the calculated bypass ratio to the measured parameters.

SYMBOLS

A	flow area, ft^2
c_p	rate of change of enthalpy with respect to temperature, Btu/lbm/^{o}R
h_{lf}	enthalpy of the liquid fuel, Btu/lbm
h_t	total enthalpy, Btu/lbm
HV	lower heating value, Btu/lbm
P_t	total pressure, lbf/ft^2
T_f	fuel temperature
T_t	total temperature, ^{o}R
W	mass flow, lbm/sec
Wa_c	airflow entering engine core, lbm/sec
Wa_e	total airflow entering engine, lbm/sec
Wa_f	discharge airflow at fan, lbm/sec
Wf_e	fuel flow, lbm/sec
Wg_c	gas flow at turbine discharge, lbm/sec

<u>Subscripts</u>

2	parameter at engine inlet
7	parameter at turbine discharge
25	parameter at fan discharge

<u>Superscript</u>

prime	parameter including error in a measured temperature

SECTION I

INTRODUCTION

In order to assess the performance and stability characteristics of a turbofan engine, the bypass ratio (BPR) must be known. The most straightforward and accurate approach to a determination of BPR is to measure the total engine airflow and the airflow through some part of the engine. Making these measurements requires considerable instrumentation in addition to the standard engine instrumentation. In addition, an accurate determination of BPR by the conventional procedure requires that all bleeds be known. Controllable bleeds are generally closed during test runs to determine BPR, but engines using compressor air to cool the turbine require cooling air continuously. Consequently, the bleeds cannot be closed and the turbine cooling air flow rate must be obtained. Data on turbine cooling air flow rate is frequently inadequate, and that which is available is often suspect. Therefore, some other method for determining BPR is needed.

This report presents a method for determining BPR that eliminates the need for ascertaining the turbine cooling air flow rate. It is simpler and less costly, since the only instrumentation required in addition to standard engine instrumentation is that required to measure the fan discharge total temperature. This method was applied to data for the TF30-P-1 engine and the results are plotted and analyzed for a series of simulated flight conditions. Repeatability of test results indicates accuracy is very good.

SECTION II

CALCULATION PROCEDURES

1. CHOKED TURBINE NOZZLE DIAPHRAGM METHOD

The conventional method of determining BPR is based on the flow parameter at the turbine nozzle diaphragm. The flow is measured here because the impact of error on the calculated flow parameter determined from pressure and temperature measurements is essentially inversely proportional to the flow Mach number; therefore, measurements of pressure and temperature should be made at a point where the flow Mach number is high and, preferably, where it is known, as is the case at the turbine nozzle diaphragm. Thus, the procedure is known as the choked turbine nozzle diaphragm method. The flow parameter is $\frac{W\sqrt{T_t}}{A\ P_t}$, where

(a) T_t, the total temperature, is calculated from fuel flow and compressor temperature,

(b) P_t, the total pressure, is either measured directly or is determined by measuring the compressor discharge pressure and assuming a pressure drop across the burner, and

(c) A, the minimum flow area, is determined from design data.

2. ENERGY EQUATION METHOD

The underlying theory for this method is quite straightforward and involves nothing more than using the energy equation and the continuity equation for the flow through the engine. Thus the procedure involves two equations and two unknowns, so no iteration is required.

The solution to these equations depends upon the split in the airflow, as depicted in Figure 1. To determine the split in the airflow, we need measurements for the following parameters:

(a) Total engine airflow, Wa_e

(b) Engine inlet total temperature, T_{t2}

(c) Fan discharge total temperature, T_{t25}

(d) Fuel flow, Wf_e

(e) Fuel temperature, T_f

(f) Turbine discharge total temperature, T_{t7}, and

(g) Fuel lower heating value, HV.

The energy equation is then written:

$$Wa_e \times h_{t2} + Wf_e\,(h_{lf} + HV) = Wa_f \times h_{t25} + Wg_c \times h_{t7} \tag{1}$$

The continuity equation is:

$$Wa_e + Wf_e = Wa_f + Wg_c \tag{2}$$

Substituting the continuity equation into the energy equation and rearranging yields:

$$Wa_c = Wa_e \left[\frac{h_{t2} + \dfrac{Wf_e}{Wa_e}(h_{lf} + HV) - h_{t25} - \dfrac{Wf_e}{Wa_e}(h_{t7})}{h_{t7} - h_{t25}} \right] \tag{3}$$

and

$$Wa_f = Wa_e - Wa_c \tag{4}$$

The bypass ratio, BPR, can then be determined from

$$BPR = \frac{Wa_f}{Wa_c} \tag{5}$$

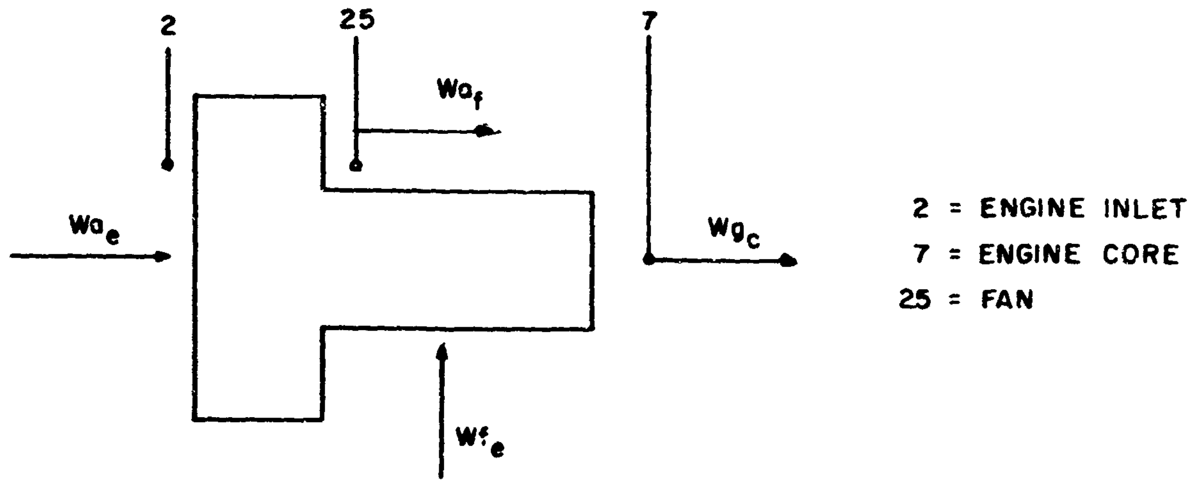

Figure 1. Schematic of Engine Showing Station Designation

SECTION III

RESULTS OF THE CALCULATION

The accuracy of the calculation method outlined in Section II was tested by applying the proc dure to data for a specifc engine. Data of the TF30-P-1 engine collected in tests conducted at the Naval Air Propulsion Test Center were used for this calculation. BPR was determined under varying conditions of Mach number and altitude, and the results in terms of BPR versus EPR (engine pressure ratio) are plotted in Figure 2. The consistency of the calculated BPR at the different Mach number and altitude conditions indicates the method is valid.

Analysis of these results indicates that the bypass ratio is not uniquely ependent on engine pressure ratio. There is a nongeneralization of data which is ascribed, in pa , to an inadequacy of the instrumentation. There is generally a considerable variance in the mperature gradients at the turbine discharge (Station 7). Consequently, a substantial amount of instrumentation was used at Station 7 to measure turbine discharge temperature, and an arithmetic average of the probe readings was made to account for the variance. An arithmetic average of the individual probe readings, however, probably was not representative of the average temperature at all power settings. The instrumentation used in the tests that provided the data for these calculations is shown in Figure 3.

Tests are now being conducted on a TF30-P-3 engine in which twice as much instrumentation is being used in the fan duct as was used in the tests of the TF30-P-1. This additional instrumentation is expected to provide more accurate measurements of fan discharge total temperature, which is expected to provide more accurate computations of BPR.

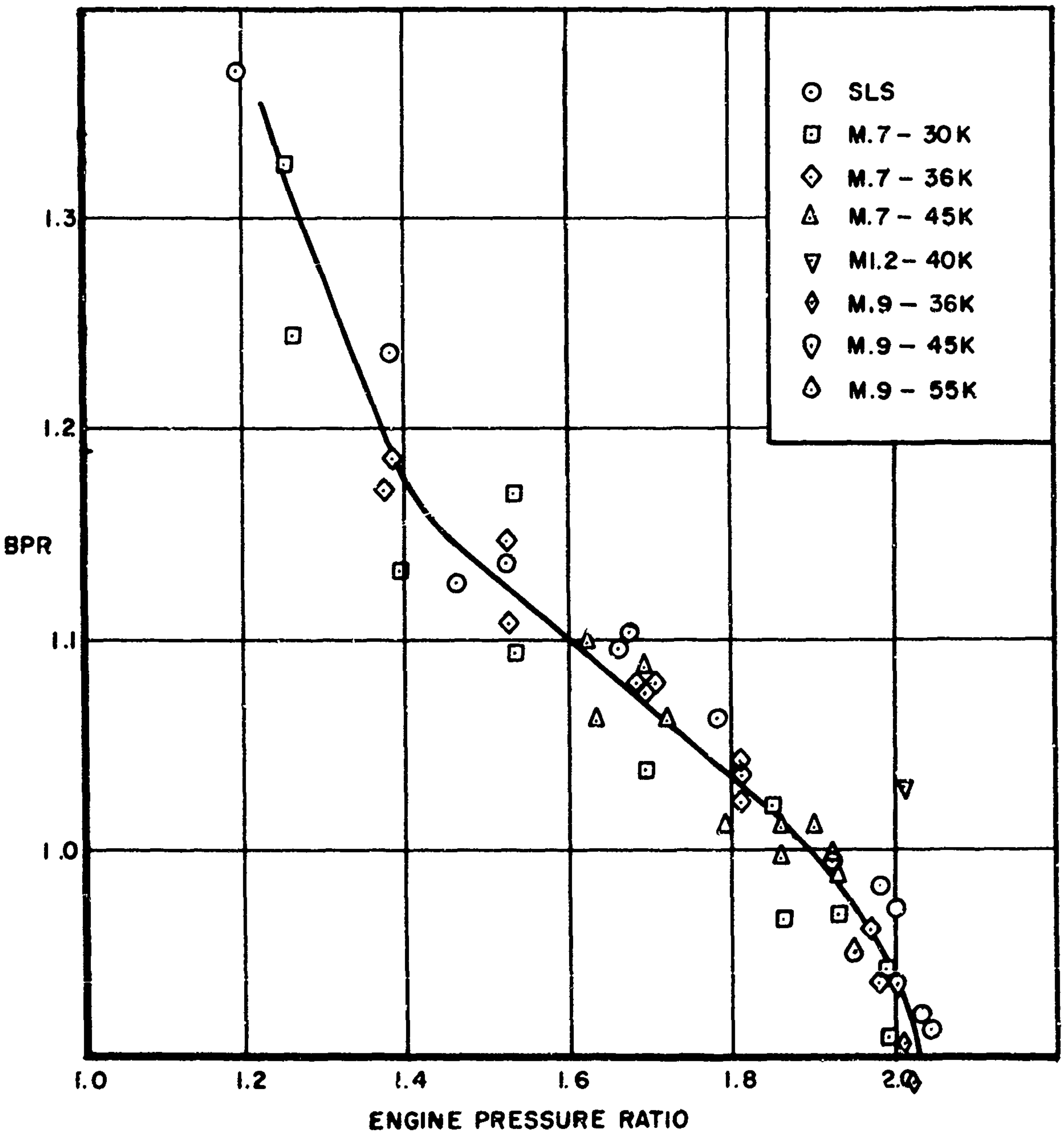

Figure 2. Bypass Ratio vs. Engine Pressure Ratio

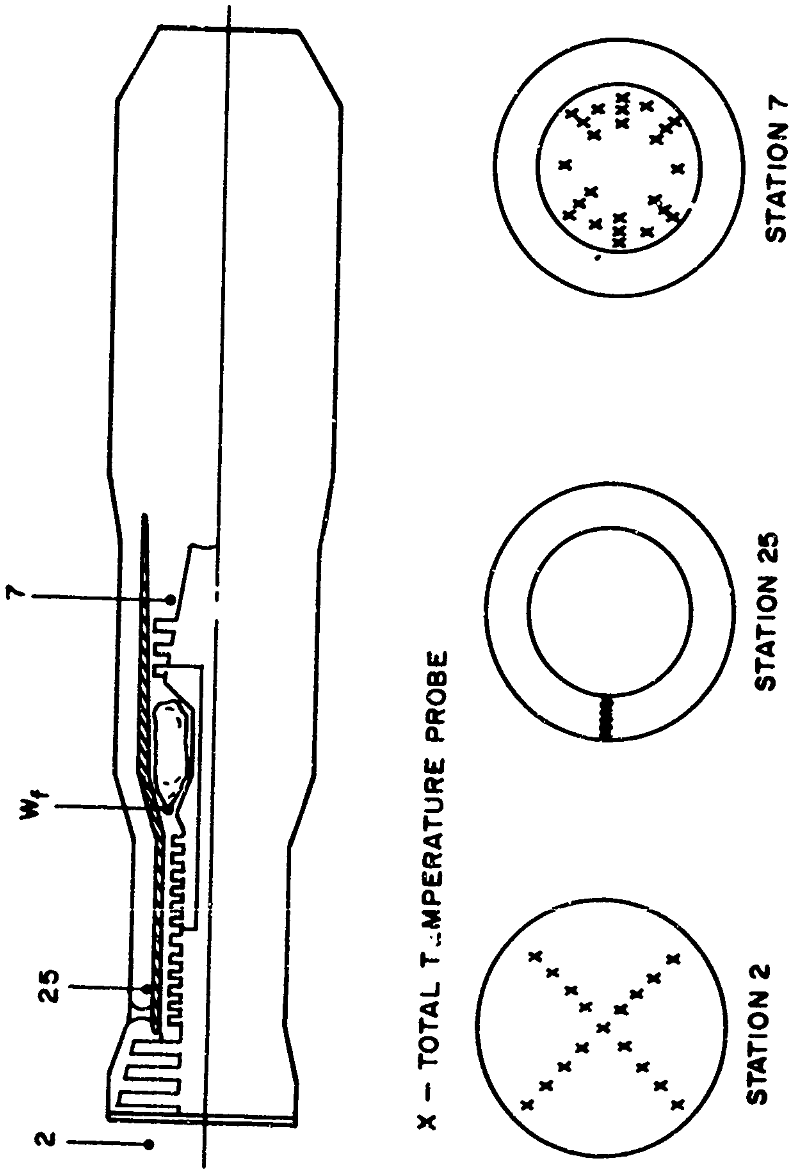

Figure 3. Instrumentation Diagram

SECTION IV

SENSITIVITY ANALYSIS

The sensitivity of the calculated bypass ratio to the accuracy of the measured parameters is of particular interest in this analytical exercise. The analytical portion of this investigation was directed toward determining those parameters which have first order effects on the accuracy of the calculated bypass ratio. Those parameters that also affect the bypass ratio when calculated by the choked turbine nozzle method, however, were not considered (e.g., the accuracy of total engine airflow, fuel flow, fuel heating value).

No temperature gradients of any consequence were found at Station 2, so no temperature gradients were expected at the fan discharge. However, small gradients in this measurement affect the calculation considerably, so more instrumentation to measure this parameter would have provided better data for this technique.

Obtaining an average total temperature at the turbine discharge (T_{t7}) was the biggest problem, so the greatest amount of instrumentation was used for this measurement. Since T_{t7} is large, however, small errors in the measurement of this parameter affect the calculated bypass ratio less than equivalent errors in other measurements.

The sensitivity of c_p, the rate of change of enthalpy with respect to temperature, is so small over the temperature band 50 to 100°R that it is treated as a constant in this analysis. This is not to say that c_p does not vary with temperature, but rather that, for the purposes of this analysis, changes in c_p in the expected error band of the measured temperatures will be quite small. Assuming that c_p and Wa_e are constant, the sensitivity of Wa_c/Wa_e to a 1°R variation in T_{t7}, T_{t25}, and T_{t7} can be determined from Equations 6, 7, and 8, respectively.

$$\frac{d}{dT_{t2}}\left(\frac{Wa_c}{Wa_e}\right) = \frac{1}{T_{t7} - T_{t25}} \tag{6}$$

$$\frac{d}{dT_{t25}}\left(\frac{Wa_c}{Wa_e}\right) = \frac{1}{(T_{t7} - T_{t25})^2}\left[T_{t2} + \frac{Wf_e}{Wa_e \times cp}(h_{lf} + HV) - T_{t7}\left(1 + \frac{Wf_e}{Wa_e}\right)\right] \tag{7}$$

$$\frac{d}{dT_{t7}}\left(\frac{Wa_c}{Wa_e}\right) = \frac{-1}{(T_{t7} - T_{t25})^2}\left[T_{t2} + \frac{Wf_e}{Wa_e \times cp}(h_{lf} + HV) - T_{t25}\left(1 + \frac{Wf_e}{Wa_e}\right)\right] \tag{8}$$

Then, using the sensitivity of Wa_c/Wa_e, we can determine the sensitivity of the bypass ratio from the following equations:

$$Wa_c' = Wa_e - Wa_c - \Delta Wa_c \tag{9}$$

$$Wa_f' = Wa_e - Wa_c' \tag{10}$$

$$BPR' = Wa_f' / Wa_c' \tag{11}$$

The accuracy of these expressions was evaluated by inserting test data for the TF30-P-1 engine and assuming a nominal value of 0.26 for c_p. An error of +1°R in T_{t2}, T_{t25}, and T_{t7} caused an error in the calculated bypass ratio of -0.6%, +0.4%, and +0.3%, respectively.

SECTION V

CONCLUSIONS

When adequate instrumentation is not available to provide sufficient data for calculating the bypass ratio of an engine by means of the choked turbine nozzle diaphragm method, the method outlined herein can be used. The repeatability of the calculations is good, as shown in Figure 2.

This method, which uses the energy equation for determining the bypass ratio, does not require an accurate measurement of the turbine cooling air or the flow area. The only extra instrumentation required (i.e., total temperature probes downstream of the fan exit) can generally be installed through fan duct ports after the engine is installed. This method is less time-consuming and costly than the existing method of determining bypass ratio, but the instrumentation used should be of significantly higher reliability because no additional hot section instrumentation is used.

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